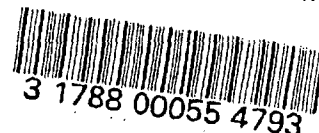


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RESPONSE OF STRUCTURES TO BLAST: A NEW CRITERION

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ABSTRACT. Distributed energy explosions and lumped energy explosions are examined in terms of two damage criteria currently in use: (1) the peak overpressure and (2) the positive impulse per unit area. From these two diverse and partially contradicting items, the concept is developed that a suitable index for the damage potential of explosive blast is the impulse per unit area that it can deliver within some critical time.



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FOREWORD

The study described in this report is one of a series made as part of a continuing applied research program at the Naval Weapons Center in support of explosive ordnance problems.

Dr. Gilbert Ford Kinney, coauthor of the report and Professor of Chemical Engineering at the U.S. Naval Postgraduate School, Monterey, performed his studies at the Naval Weapons Center, sponsored by the Detonation Physics Division, Research Department.

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Because of the continuing nature of the explosive ordnance studies being made at the Center, refinements and modifications may later be made in the methods and the measurements discussed.

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DISTRIBUTED ENERGY AND LUMPED ENERGY EXPLOSIONS

A fuel-air explosion, for example one from a gasoline vapor and air mixture, is characterized by the circumstance that the explosive energy is initially distributed and released throughout a relatively large volume. This contrasts with an explosion from a material such as dynamite where the energy release is initially concentrated into a relatively small volume.

Important aspects of distributed energy explosions include (1) how these explosions compare and contrast with concentrated energy explosions, particularly with regard to respective damage potentials, and (2) what constitutes a valid index or criterion for damage potential. Reported here are the results of both theoretical and experimental studies made in these connections. Excellent correlation between theoretical considerations and experimental measurements has been obtained, largely through a new damage criterion for blast damage potential. This proposed new criterion appears to have substantial utility in the study of both distributed energy and concentrated energy explosions.

CONVENTIONAL DAMAGE CRITERIA

A key aspect in the study of explosions is the criterion used as an index of their damage potential. Consider first the situation where a conventional and typical criterion for blast damage potential, the peak overpressure, is used. The scaling laws for explosions (Ref. 1, 2, and 3) state that the developed peak overpressure is a unique function of a "scaled" distance (see Appendix).

This observation may be stated alternatively to the effect that the radial distance to which a specified peak overpressure extends, r_p , varies directly with the cube root of the explosive energy release, W . Then the area covered by a specified peak overpressure, A_p (or πr_p^2), becomes

$$A_p = \pi k^2 W^{2/3} \quad (1)$$

where k is the constant of proportionality for the distance relation.

In the situation where the explosive charge is divided into n equal fractional charges, the area covered by each of these fractional charges, A_P' , becomes

$$A_P' = \pi k^2 (W/n)^{2/3} \quad (2)$$

The total of n such areas is the area covered by the specified peak overpressure when the charge is distributed into n segments and there is negligible overlapping or mutual interference. The relationship between the total areas for the two situations is the ratio

$$\frac{\text{area for distributed charge}}{\text{area for lumped charge}} = n A_P' / A_P = n^{1/3} \quad (3)$$

This relation states implicitly that the damage effectiveness of the distributed energy explosion is increased over that of the lumped energy explosion by the cube root of the number of segments into which the charge is divided.

Conclusions such as this have at times been used as arguments for the tactical use of distributed charge weapons rather than lumped charge ones. However, the relation cannot hold as the number of segments increases indefinitely. Then the computed area approaches infinity, whereas no finite amount of explosive can cover an infinite area. It is this very situation, however, that is approached by the molecular dispersion of a fuel-vapor-air explosion. It must therefore be concluded that the behavior of a distributed charge explosion is somehow different from that of a lumped charge, or else that the peak overpressure is not entirely suitable as a criterion for the blast damage potential of explosions, particularly those from distributed charges. This latter conclusion is one that is well recognized.

An alternative and possible improvement over peak overpressure as a criterion for blast damage potential has been suggested: the explosive impulse per unit area, or time integral of the overpressure. The scaling laws do not provide explicitly for a determination of the distance to which a given impulse extends. However, this may be determined indirectly as a function of the explosive energy release, by conventional methods outlined in the Appendix. Results of such computations are shown in the form of a log-log plot in Fig. 1. For a wide range of about three decades of explosive energy release, the distance to which a given impulse extends is directly proportional to the 0.60 power of the explosive energy release for side-on values, and to the 0.55 power for reflected values. For example, the area covered by a particular side-on impulse value, $A_{I,s}$, becomes proportional to $(W^{0.6})^2$, or

$$A_{I,s} = \pi k^2 W^{1.2} \quad (4)$$

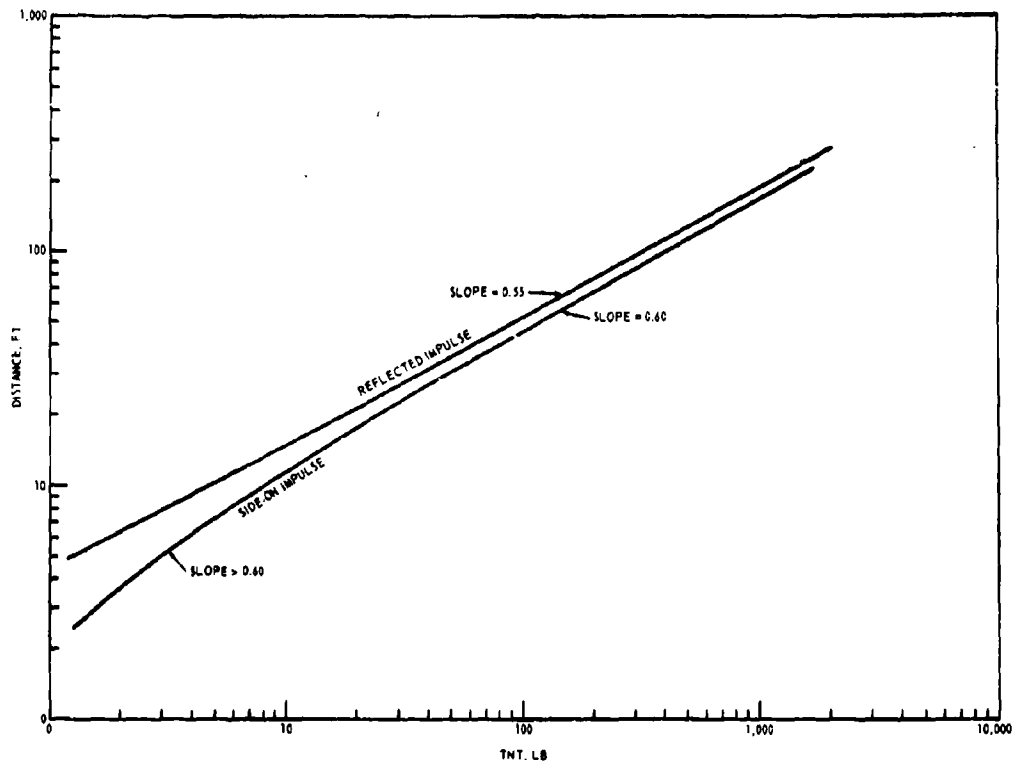


FIG. 1. Distance to Which a Given Impulse Extends Versus Explosive Yield.

where

W is the explosive energy release

k is the constant of proportionality for the distance relation

For a charge divided into n equal segments, the area covered by each segment, $A_{I,s}$, is $\pi k^2 (W/n)^{1.2}$, and that for n segments is

$$n A_{I,s} = \pi k^2 W^{1.2} / n^{0.2} \quad (5)$$

The relationship between this area and that for the lumped charge is the ratio

$$\frac{\text{area for distributed charge}}{\text{area for lumped charge}} = n^{-0.2} \quad (6)$$

This relation implies that the blast damage effectiveness of the distributed charge is reduced from that of the lumped charge by the fifth root of the number of segments into which a charge is divided. It also indicates that in the limit of a molecularly dispersed fuel-vapor-air mixture,

a negligible damage potential is reached. This is an erroneous conclusion, as every internal combustion engine with preignition knock testifies. Similar erroneous conclusions are reached if reflected impulse values are considered. Hence, it appears that impulse is not entirely suitable as a criterion for the blast damage potential of an explosion, particularly one from distributed charges. This situation also is well recognized.

NEW CRITERION FOR BLAST DAMAGE POTENTIAL

Neither of the two blast damage criteria, peak overpressure or impulse per unit area, considered in the foregoing section appears to be applicable to the study of distributed energy explosions, and certainly their conflicting implications about the effect of distributed charges cannot both be correct. Thus, in the study of distributed energy explosions, there is need for a realistic criterion for blast damage capability. It is of interest to note that the same need exists for ordinary lumped charge explosions, although this conclusion is reached through other considerations.

A detailed examination of the two conventional criteria for blast damage potential reveals that the peak overpressure criterion is deficient in that it predicts a damage capability that is the same for both very, very short disturbances and for sustained high pressures, provided only that the peak values are the same. Likewise, the impulse criterion is deficient in that it considers as damaging those small and actually undamaging overpressures that are applied over a long period of time.

To overcome these diverse difficulties, the concept is suggested that the damage potential of any explosive blast lies in its ability to deliver a sustained pressure effect, but for some minimum time. A criterion of this type can conveniently be expressed in terms of a blast wave impulse deliverable within a critical time. As such, this criterion is intermediate between the two criteria discussed previously and so escapes their mathematical difficulties in the boundary situations for a highly distributed charge.

A consequence of the proposed criterion for blast damage potential is that there must also exist for each target some critical impulse above which the target is damaged if such impulse is received within a critical time, but below which there is no effect. This proposed criterion also carries within it the important consideration that a minimum overpressure is required for a blast wave to inflict damage to a given structure, this minimum being the ratio of the critical impulse to the critical time. It is possible to calculate these critical values from basic engineering data for simple structures. It may be noted also that the proposed criterion of a critical impulse within a critical time is consistent with deductions from related studies on impact sensitivity (Ref. 4).

CRITICAL TIME

The identification and selection of the critical time within which an impulse must be received by a target to inflict damage is essentially empirical. However, some theoretical guidelines are available. Thus, for a simple system at rest but capable of harmonic motion, a maximum velocity and maximum amplitude of swing are given by an impulse of very short duration. Increasing the duration of the given impulse results in a decrease in achieved velocity and amplitude. However, this decrease is relatively small until the duration of the impulse becomes about one-quarter of the natural period of oscillation, when further increases give marked decreases in amplitude. These observations have been amply confirmed by analog computer studies (Ref. 5) as illustrated in Fig. 2.

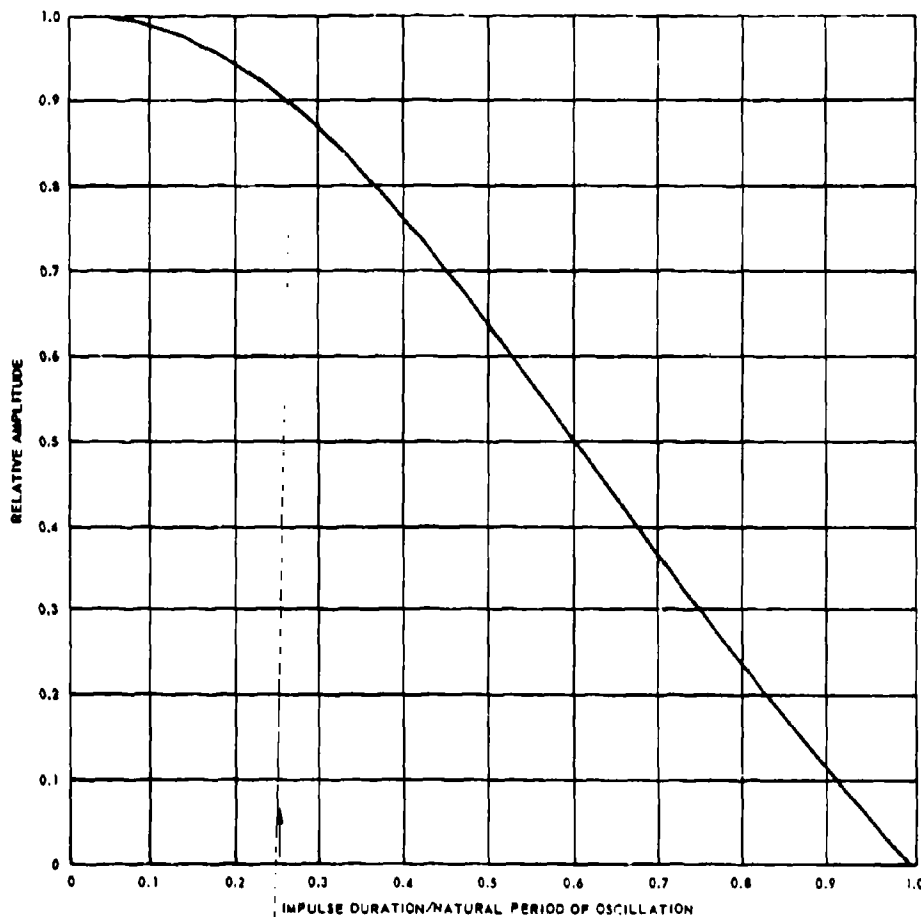


Fig. 2. Relative Amplitude of Undamped Harmonic Motion Versus Duration of Applied Impulse. Marked decreases in amplitude occur after the impulse duration reaches one-quarter of the natural period of oscillation.

In addition, it may be noted that a simple harmonic oscillator travels from zero to maximum displacement in one-quarter of its natural period and that the enforced motion of a structural member leading to damage effects should not be greatly different.

Based on these considerations, it appears that a time equal to one-quarter of the natural period of oscillation should for any structural element represent a rough sort of cutoff time for impulse effectiveness. Representative calculations based on the determination of such natural periods are discussed in the following section.

In addition to structural deformations as a form of blast damage, there is also the situation where a body such as a truck is physically displaced and hurled from its original position. The forces giving rise to such a hurling action must be sufficiently great to override the forces of gravity, and they are arbitrarily taken to be those forces which by acting for 1 second can produce the corresponding free-fall velocity. A time in the order of 1 second thus becomes the critical time for blast damage received by this hurling mechanism.

To summarize, the critical times for explosive blast damage are arbitrarily but reasonably taken as one-quarter of the natural period for structures and structural members, and 1 second for destructive hurling away of nonattached objects.

CRITICAL IMPULSE

Structural damage inflicted by explosive blast is the result of an impulsive load that exceeds the resistance of a material. In ordinary impulsive loading, a stress wave moves through the material such that

$$\sigma = \rho CV, \quad (7)$$

where

- σ is the stress
- ρ is the density
- C is the velocity of sound in the material
- V is the relative particle velocity associated with the stress wave (the product ρC is known as the "acoustic impedance")

For the limiting situation where the stresses developed equal the dynamic yield strength, there also is a limiting or critical particle velocity, V_c , which if exceeded causes permanent displacement within the material.

Experimental values for this critical particle velocity are available (Ref. 6) for the tensile failure of some of the common metals. For other materials the critical particle velocity can in principle be found from the dynamic yield strength when such dynamic yield values are known (they are appreciably greater than the conventional static values). However, blast-produced failures are seldom ones in simple tension. Hence, the

critical particle velocity applicable in the disruption of a target by blast is not so simply described, but it should be at least closely related to the critical particle velocity for failure in simple tension. For purposes here these two critical particle velocities will be considered as being identical.

For blast damage the critical particle velocity is actually a differential velocity referenced to a part of the system at rest. Consider, for example, a structural system where a skin is stretched between two rigid support members. When an impulsive load is applied, the inertia of the support members keeps them from moving significantly, while the thinner skin is accelerated to a velocity that may exceed the critical velocity, in which case tearing of the skin results. Similar considerations apply in systems that cantilever out from a massive inertial reference system, such as the empennage or the wing of an aircraft cantilevered out from the fuselage.

The critical impulse per unit area associated with the critical velocity is given by elementary considerations (Ref. 6) as

$$I_c = \rho \delta V_c \quad (8)$$

where

ρ is the density of the target material

δ is the thickness of the material

V_c is the critical velocity

The critical impulse may also be expressed in terms of the dynamic yield strength for the material by combining the above relations to give

$$I_c = \delta \sigma_y / C \quad (9)$$

where

C is the velocity of sound in the material

σ_y is the dynamic yield strength

The velocity of sound, C , can be replaced by its equivalent

$$C = \sqrt{E/\rho}$$

where

E is the modulus of elasticity

and this gives a third form for the expression for critical impulse

$$I_c = (\rho/E)^{1/2} \delta \sigma_y \quad (10)$$

These three forms of the expression for critical impulse are all expressed in coherent units and are all equivalent. The first of these would appeal to those who have worked with impulsive loads and shock waves in metals, but the others may on occasion be preferred because they contain items directly related to the ordinary strength characteristics of a material.

The above expressions apply as part of the criterion for blast damage when the damage occurs by deformations of a structure or a structural member. For the important situation where a target is damaged by being hurled bodily from its original position, the critical impulse is arbitrarily taken to be that which could cause the entire object to reach free-fall velocity in 1 second. This is convenient mathematically, and also is in accord with the observation that the corresponding fall of about 16 feet is ordinarily very damaging to most targets of interest.

REPRESENTATIVE CALCULATIONS

Values for the blast damage criterion, critical impulse within a critical time, were computed for a parked aircraft and for a light industrial building. For the aircraft, three types of damage were considered: (1) tearing the skin, (2) breaking off a wing section, and (3) physical displacement by hurling the entire plane.

AIRCRAFT SKIN FAILURE

For damage by the mechanism of tearing the skin, the critical time is taken from a computed value for the resonant frequency of this structural member. The skin was assumed to be of 1/16-inch-thick aluminum, clamped to stringers on 8-inch separation. For clamped panels of infinite length the resonant frequency, f , is given by the relation (Ref. 7)

$$f = 217,600 \times 0.985 \times \delta / b^2 \quad (11)$$

where the factor 217,600 pertains to this type of structure, and the factor 0.985 is for the type of metal.

Here

- δ is the skin thickness in inches
- b is the distance of spacing in inches

Thus,

$$f = 217,600 \times 0.985 \times (1/16)/(8)^2 = 209 \text{ cps} \quad (12)$$

This resonant frequency corresponds to a natural period of vibration of $1,000/209 = 4.8$ milliseconds, and to a critical time of $4.8/4 = 1.2$ milliseconds.

The critical impulse required for tearing the skin is computed in any one of three separate ways, depending on the primary data available.

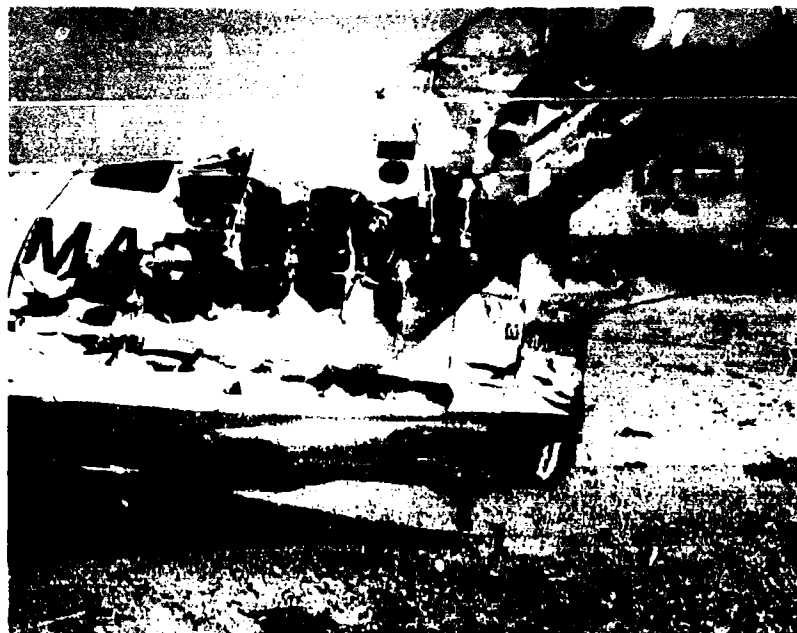


FIG. 4. Typical Aircraft Skin Failures.

The computed minimum overpressure for this damage becomes $43/1.2 = 36$ psi, which must persist for at least as long as 1.2 milliseconds to provide the necessary minimum impulse.

AIRCRAFT WING BREAK-OFF

In calculations of values for tearing off sections such as the empennage or the wing of an aircraft, the first problem is that of determining the resonant period of the structure. This in principle can be done through use of conventional formulas for cantilevered beams (Ref. 7), but complications such as the stiffening action of various braces make such computations unreliable. Hence, experimentally determined values should be used whenever such data are available. In a generic type aircraft (Ref. 9) of reasonably small dimensions, the resonant frequency for the wing and empennage sections is known to be approximately 5 cps. This corresponds to a period of 200 milliseconds and gives a critical time represented by the quarter period as about 50 milliseconds.

For an estimate of the critical impulse, the major resistance of the wing or empennage section is assumed to be that of two skin sections, ignoring the support members. This gives the critical impulse value for wing break-off as $2 \times 43 = 86$ psi-ms.

A schematic of a typical wing break-off is shown in Fig. 5.

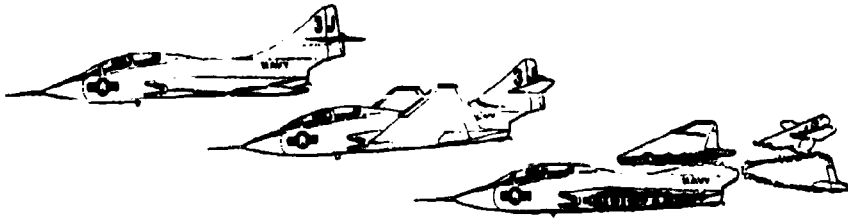


FIG. 5. Progressive Stages of Aircraft Wing Break-Off. Computed critical impulse, 86 psi-ms; computed critical time, 5 milliseconds.

TUMBLED AIRCRAFT

The critical value of impulse for tumbling a total aircraft (I_{CT}) is based on the assumption of achieving free-fall velocity at 1 second. On this basis the critical time is taken arbitrarily as 1 second, or 1,000 milliseconds. The critical impulse thus becomes the product of the mass and the free-fall velocity of 32.2 fps.

The total mass of the object in pounds is converted to a mass in slugs by dividing by 32.2. Then multiplying by the assigned free-fall velocity gives the total impulse, in pounds force-seconds, that numerically equals the mass in pounds. Dividing by the area provides, with proper conversion factors, a specific impulse in pounds per square inch-milliseconds.

The typical total mass of a generic fighter aircraft (Ref. 9) may be taken as 15,000 pounds mass, corresponding to a total critical impulse of 15,000 lbf-sec. The following values are chosen for three typical aircraft areas:

Maximum area with both wings and fuselage seen, 500 ft². The critical impulse is then

$$I_{CT} = (15,000 \times 1,000) / (500 \times 144) = 208 \text{ psi-ms} \quad (16)$$

Side-on fuselage-only area, 200 ft²

The critical impulse on the fuselage only (I_{CF}) is

$$I_{CF} = (15,000 \times 1,000) / (200 \times 144) = 521 \text{ psi-ms} \quad (17)$$

Minimum area, directly head on, 50 ft²

The critical impulse head on (I_{CH}) is

$$I_{CH} = (15,000 \times 1,000) / (50 \times 144) = 2,080 \text{ psi-ms} \quad (18)$$

The value chosen for the actual target would probably be a weighted average of these attack situations and would be in the range of 500 to 1,000 psi-ms.

An aircraft hurled bodily from its position is indicated schematically in Fig. 6. The resulting damage, however, comes about largely as a

result of its subsequent collision, either with buildings, other aircraft, or the ground.

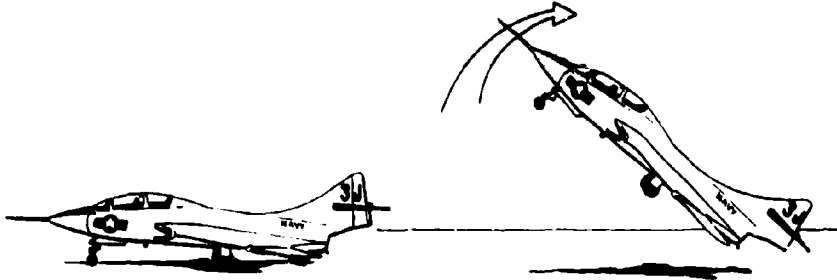


FIG. 6. Progressive Stages of Aircraft Tumbling When Ordinary Forces of Gravity Are Overridden. Assumed critical time, 1,000 milliseconds; weighted average critical impulse, 500 to 1,000 psi-ms.

LIGHT INDUSTRIAL BUILDING

A structure of interest is a light industrial building similar to one used at the Nevada test site in tests for the effects of nuclear weapons, (Fig. 7). This rigid steel frame building is about 60 feet long and 15 feet high, with the walls divided into panels each 5 feet high and 20 feet long. The skin is of aluminum about 0.040-inch thick, with vertical ribs folded out of the material every 18 inches. In such a building there are many different resonant frequencies and many critical impulses; attention here is limited to possible skin rupture.



FIG. 7. Typical Light Industrial Building. Computed critical impulse for tearing the skin, 29 psi-ms; computed critical time, 9.1 milliseconds.

The skin of the building is treated as a panel 18 inches by 5 feet of 0.040-inch-thick aluminum supported along the four edges. The resonant frequency is given by the relation (Ref. 7)

$$f = 225,600 \times 0.985 \times \delta / b^2 = 225,600 \times 0.985 \times 0.040 / (18)^2 \\ = 27.4 \text{ cps} \quad (19)$$

where

s is the skin thickness, in inches

b is the minor dimension, in inches

The constant 225,600 applies to a system with the specified ratio of length to width, and the constant 0.985 corrects for aluminum. This resonant frequency represents a critical time of $1,000/(27.4 \times 4) = 9.1$ milliseconds.

The critical impulse for a panel of this thickness becomes

$$I_c = 5.23 \times 0.040/12^3 \times 240 = 29 \text{ psi-ms} \quad (20)$$

where 5.23 is the density, and 240 fps is the critical velocity for aluminum.

A summary of the calculations is given in Table 1.

TABLE 1. Summary of Calculated Values.

Effect	Critical time, ms	Critical impulse, psi-ms	Minimum mean overpressure, psi
Tearing skin of aircraft	1.2	43	36
Breaking off aircraft wing . . .	50	86	1.7
Bodily hurling aircraft:			
Maximum area effective. . .	1,000	208	0.2
Side-on fuselage area	1,000	521	0.5
Minimum area	1,000	2,083	2.1
Weighted average	1,000	500-1,000	0.5-1.0
Tearing skin of light industrial building	9.1	29	3.2

RESULTS

In analyzing and comparing results of the above representative calculations, several aspects are of interest. For example, the impulse calculated as being required to bodily hurl a parked aircraft, if applied quickly to only a part of the structure, would almost always result in severe localized damage. Thus, the blast from two different explosions even though showing the same impulse might well cause two entirely different types of damage. From such considerations, it develops that a nuclear explosion near the limits of its damage effectiveness with a wide-spread region of blast overpressure and relatively long duration might be expected to damage targets such as a parked aircraft by the tumbling mechanism. In contrast, a conventional explosion with a shorter range and relatively short duration might well be expected to cause damage more by the mechanism of severe localized stresses (Fig. 8). Localized damage of such limited extent would not be expected from a distributed energy explosion even though the energy release is the same.



FIG. 8. Highly Localized Damage by Blast From a Lumped Charge Explosion.

Another consideration with the proposed damage criterion is that the ratio of critical impulse to critical time represents a minimum mean overpressure to be exceeded if damage is to occur. From this viewpoint an overpressure of about $1,000/1,000 = 1.0$ psi (the exact value depends on aircraft orientation) and sustained for about 1 second might be expected to damage a parked aircraft by a hurling or tumbling mechanism. For tearing the skin, however, a minimum mean overpressure of $43/1.2 = 36$ psi is indicated, but for the very short time of 1.2 milliseconds. These predicted values of minimum mean overpressures for damage appear in these instances to be reasonably in accord with experimental observations.

Consider next the computations for the light industrial building. Here a minimum mean overpressure of $29/9.1 = 3.2$ psi (for at least 9.1 milliseconds) is indicated as being required if rupture of the skin is to occur. Experimental results (Ref. 2) for a nuclear blast of presumably long duration show that a peak side-on overpressure of 3.1 psi does not rupture the skin on the roof of such a structure when it is exposed to this overpressure during a test (Fig. 9) This is a gratifying agreement with prediction.

In the same blast situation, however, the face of the structure toward the explosion is completely ruptured and torn away. But in this instance, the front face experiences an actual overpressure (in a Mach stem) that is the reflected overpressure rather than the side-on. This maximum reflected overpressure is calculated (Ref. 3) to be about 6.7 psi. Such a reflected overpressure exceeds the predicted minimum of 3.2 psi, and if maintained sufficiently long should completely disrupt the skin. This actually occurred, which again agrees with prediction. It

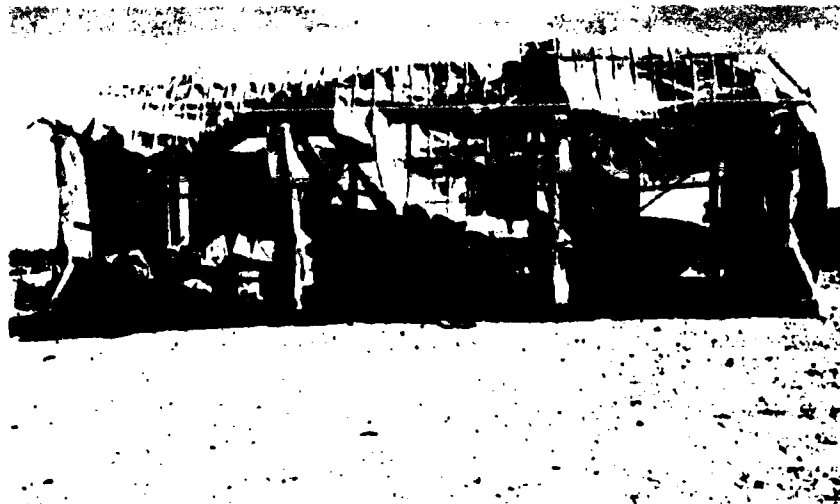


FIG. 9. Widespread Damage to Light Industrial Building by Blast From a Nuclear Explosion.

should be noted, however, that the preceding calculations of both minimum time and minimum impulse on which these comparisons are based are sensitive to the thickness of the skin involved. This observation may be stated alternatively in the form that the blast resistance of a structure depends very much on the strength of its component elements.

These examples are concerned primarily with situations where characteristics of the explosion are known. For distributed charge explosions, however, the situation may be less simple, for here the overpressure-time-distance relation is an involved one and depends among other things on the geometry of the explosion. This is illustrated in Fig. 10, which shows successive frames of a high-speed motion picture of a planar explosion. It is evident that the explosion products are moving far more rapidly in a direction normal to the plane of the explosion than in other directions; hence, the blast is more severe in this direction. A complete theoretical analysis of this phenomenon has not yet been made; therefore, experimental data are required to assess the associated damage potential. Furthermore, to obtain meaningful data in such circumstances, it seems necessary to utilize both electrical (electronic) and photographic methods. From such methods, and using the concept of critical impulse within a critical time, the damage potential may readily be found. With regard to these items, it is of interest to note that at distances only moderately removed from a distributed explosion, the peak overpressure contours rapidly approach the spherical. In this situation the explosion behaves essentially as a lumped charge explosion, and its damage potential may be estimated from conventional values for lumped charges. As a rough approximation, at distances some 5 to 10 times its longest dimension, a distributed charge shows lumped charge behavior.

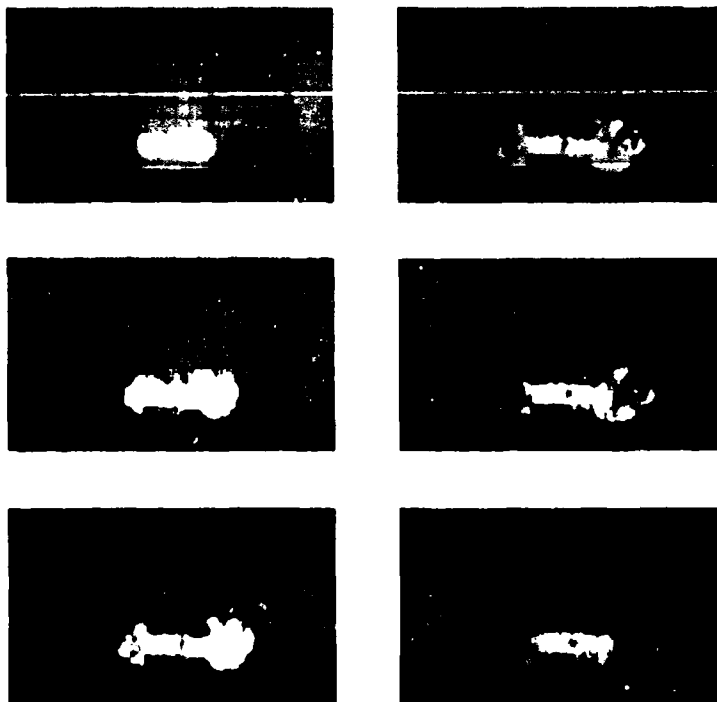


FIG. 10. Unsymmetrical Blast Wave From a Distributed Charge Planar Explosion. Successive exposures are at intervals of about 0.34 milliseconds; apparent grid spacing is about 1 foot.

CONCLUSIONS

Ideally in predicting blast damage results, in establishing a test program for blast parameters, or in assessing blast damage effectiveness, the complete dynamic response of the target, the complete aerodynamic characteristics of the target in its environment, and the exact pressure, time, and position characteristics of the blast wave are required. In practice, however, it is exceedingly difficult to obtain all of these items with sufficient accuracy to make detailed computation and analysis possible or, at times, even desirable.

A proposed criterion, critical impulse in a critical time, does take into account some of the principal effects that predominate in the equations of motion of the target when subjected to an impulsive load. Thus, this is an approach to an absolute criterion for damage susceptibility based on the fundamental characteristics of the target: its material, its material behavior, its mode of construction, and the related modes of vibration.

When this criterion for damage susceptibility is applied, the damage potential of an explosive blast for any specified target is readily obtained. This is not a simple function of peak overpressure alone, nor of impulse alone, but is a combination of overpressure, decay characteristics of the blast wave, and the dynamic response of the target structure. It should be emphasized, however, that such a damage potential should be regarded as applicable only to a general situation and should not be considered as replacing a detailed analysis that can be applied to a specific target in a specific encounter.

This new index of damage potential is related to the conventional peak overpressure index in that the new criterion contains an estimate of a minimum overpressure required for damage to a specified target. Examination of such minimum overpressures reveals that a given overpressure, if generated in a large explosion, has a greater damage potential than if generated in a small one, an item of possible concern when the hazards of stored explosives are considered.

A further application for this new criterion for blast damage potential lies in an inverse situation where it is desired to provide for maximum resistance to blast. Thus, for a parked aircraft simple precautions such as standard tie-downs to prevent tumbling are helpful in providing resistance to large explosions. For structures it is indicated that tight, well-knit structural elements with high natural frequency of vibration are helpful in that they show a short critical time. More important perhaps is that adequate strength in all elements of a structure is required if the structure is to withstand explosive blast.

Appendix APPLICATIONS OF THE SCALING LAWS FOR EXPLOSIONS

The scaling laws for explosions are based on the principle of geometric similarity and on the observation that explosive energy dispersal in a uniform atmosphere is a volume effect proceeding equally in three dimensions. Then the distances for corresponding effects, for example the same overpressure ratio, become proportional to the cube root of the explosive yield. This leads to a definition of scaled distance as

$$(\text{scaled distance}) = (\text{actual distance})/(\text{yield factor})$$

where

$$(\text{yield factor}) = (\text{explosive yield})^{1/3}$$

for different explosions in the same atmosphere. In this situation specifying an overpressure also specifies the scaled distance. The radial distance to this specified overpressure, r_p , becomes

$$r_p = W^{1/3} \quad (21)$$

where W is the explosive yield, and the required proportionality constant becomes the defined scaled distance. This proportionality is the basis for Eq. 1.

For consideration of the distances that give the same impulse effects, it is convenient also to introduce a parallel concept of scaled time, as,

$$(\text{scaled time}) = (\text{actual time})/(\text{yield factor})$$

Then from the definition of impulse per unit area as the time integral of the overpressure, the positive impulse per unit area for the explosive blast becomes

$$\left(\frac{\text{impulse per}}{\text{unit area}} \right) = \left(\frac{\text{peak}}{\text{overpressure}} \right) \left(\frac{\text{decay}}{\text{factor}} \right) \left(\frac{\text{scaled}}{\text{duration}} \right) \left(\frac{\text{yield}}{\text{factor}} \right)$$

The decay factor of this relation accounts for the quasi-exponential decay of the blast and is a function of scaled distance. The required calculations proceed by specifying a positive impulse per unit area, followed by selecting several scaled distances of interest. Then for each scaled

distance the peak overpressure, the decay factor, and the scaled duration are obtained for the corresponding reference explosion. From these, the yield factor is computed by the above relation, and then both explosive yield and actual distance to the specified impulse value are readily found.

For purposes here the values selected were those for a spherical charge of TNT explosive (Ref. 3). For side-on impulse calculations, peak side-on overpressures are found directly in the tables of Ref. 3. For the reflected impulse it was assumed that the side-on impulse is augmented during the reflection by a factor equal to one-half the reflection coefficient for the peak side-on overpressure.

The distances corresponding to a specified impulse were thus computed as a function of explosive energy release, and plotted to log-log coordinates in Fig. 1. A nearly straight-line relationship is indicated. The distance ($r_{I,s}$) traversed by a specified positive side-on impulse per unit area corresponds closely to the following empirical algebraic relation:

$$r_{I,s} \propto W^{0.6} \quad (22)$$

Similarly, for reflected impulse

$$r_{I,R} \propto W^{0.55} \quad (23)$$

The first of these proportionalities is the basis for Eq. 4. Identical proportionalities, but requiring a different constant of proportionality, are obtained if other (but constant) values of impulse are selected.

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